Net-Zero Energy Residential Test Facility

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Why Buildings’ Energy Use Is Important

The combined residential and commercial buildings sector is the largest energy consumer in the U.S.

40% of U.S. Primary Energy Consumption

- 72% of U.S. Electricity
- 55% of U.S. Natural Gas

U.S. spends $515B/year in energy costs for operation and use of constructed facilities.
What is a Net-Zero Energy Building?

- Building that Produces as Much Energy as it Consumes
- Typically Connected to the Electric Grid
- Buys Energy from the Grid when Demand exceeds Production
- Sells Energy to Grid if Production Exceeds Demand
- Production Generated using Renewable Sources (Solar, Wind)
Five Steps to Net-Zero Energy

1. Well-Insulated and Air-Tight Building Envelope
2. Place Heating/Cooling Equipment within Conditioned Space
3. Provide Controlled Ventilation
4. Select Energy Efficient Equipment/Appliances
5. Add Renewables
The Building Envelope

- Physical Separation Between Indoor Conditioned Space and Outdoor Unconditioned Space
- Provides Resistance to Air, Moisture, and Heat Movement
- Make as Insulated and Air-Tight as Possible
Place Heating/Cooling Equipment within Conditioned Space

- Conditioned Space Means Heated or Cooled Space
- Place Heating/Cooling Equipment/Ducts in Conditioned Space
- Energy Losses from Ducts are Significant
Provide Controlled Ventilation

- Build Thermal Envelope as Tight as Possible
- Bring In Fresh Outdoor Air while Exhausting Stale Air
- Transfer Heat from Stale Exhaust Air to Incoming Fresh Air (Heating)
- Transfer Heat from Incoming Fresh Air to Exhaust Stale Air (Cooling)

“Build Tight, Ventilate Right”
Select Energy Efficient Equipment

- Space Conditioning (Heating/Cooling Equipment)
- Appliances
- Lighting
- Plug Loads
Finally - Add Renewables

- Photovoltaic Systems Convert Sunlight into Electricity
- Most Systems are Grid-Connected and Do Not Incorporate Energy Storage
- “Smart Meter” Captures Flow of Energy in Both Directions

- Solar Thermal Systems Convert Sunlight into Hot Water
- In Freezing Climates a Heat Exchange and Anti-Freeze Solution is Needed
- A “Back Up” Water heater is Needed for Cloudy/Rainy/Snow Conditions
Net-Zero Energy Residential Test Facility
Project Specifics

- Type: Single-Family
- Stories: 2
- Bedrooms: 4
- Baths: 3
- Floor Area: 2,709 sq. ft.
- Basement Area: 1,518 sq. ft.
- Smart Grid Ready
- Electric Vehicle Ready
- Four-Member Family

http://www.nist.gov/el/nzertf/
NZERTF Objectives

- Demonstrate Net-Zero Energy for a Typical Home
- Provide “Real World” Field Data to Validate/Improve Computer Energy and Indoor Air Quality Computer Simulation Models
- Provide a Realistic Test Bed to Develop Improved Methods of Test for Energy Efficient Technologies
- Evaluate Emerging/Innovative Building Energy Technologies
NZERTF Envelope Design

- R-Value is a Measure of Thermal Resistance
  Heat Transfer/Unit Time (ft^2 F hr)/Btu or (m^2 K)/W

- Roof Assembly R-72 (Typical R-38)

- Exterior Walls R-45 (Typical R-13)

- Windows R-5.3 (Typical R-2.9)

- Rim Joist Area R-35 (Typical R-13)

- Basement Walls R-23 (Typical R13)

- Basement Slab R-10 (Typical R10 Two Foot In)

Typical values - 2009 International Energy Conservation Code Climate Zone 4
NZERTF Roof Construction

5" foil-faced polyisocyanurate insulating sheathing in three layers (1 1/2", 2", 1 1/2"};
extend outer edge of roof overhang; joints staggered
Continuous fully-adhered air barrier
continuous with membrane over wall sheathing
1/8" plywood sheathing with H-clips

3/8" plywood roof sheathing with H-clips;
attach to roof framing using galvanized
wood screws (min. length 7/8"
Fully-adhered peel and stick roof membrane
Asphalt roof shingles
1 1/2" x 3 1/2" lookout framing at 24" o.c.
with two layers of insulating sheathing

11 1/4" LSL roof rafter
11 1/4" netted cellulose insulation
1/2" gypsum wall board; painted with latex paint
Bottom of ceiling joist
Continuous rim board
1/8" plywood wall sheathing
Continuous fully-adhered air barrier membrane over
plywood sheathing
Stainless steel drip edge
3" crown moulding
3/8" x 8" trim board
3/8" plywood
3/8" beadboard soffit
1" x 8 1/2" frieze board
Extend insulating sheathing on wall up to
plywood on underside of roof insulating sheathing; joints staggered and taped on outer layer
NZERTF Exterior and Basement Wall

1/8" plywood covered with continuous fully-adhered air barrier membrane

Two layers of foil-faced polyisocyanurate rigid insulation; joints staggered; joints on outer layer taped

Fiber cement siding

Liquid-applied capillary break

2x4 treated plate

Grade

Open-cell spray foam insulation

Foundation wall

Damproofing on foundation wall

Polypropylene mesh strip

Aluminum coil stock

Insect screen
NZERTF Porch to Wall Connection
NZERTF Basement Slab Detail

Continuous fillet bead of urethane sealant between 2" XPS bond break and foundation wall
Continuous fillet bead of urethane sealant between 2" XPS bond break and concrete slab
2" XPS bond break
4" concrete slab with welded wire mesh placed at mid-depth
6 mil polyethylene vapor barrier
2" XPS rigid foam slab insulation
Embedded hydronic tubing

Free-draining backfill
Liquid-applied capillary break (must dry tack-free) applied on top of footing prior to placing/casting concrete foundation wall
Keyway
Filter fabric placed under perimeter drain and wrapped around gravel
Coarse gravel (no fines)
4" PVC pipe through bottom of footing connecting interior and exterior gravel beds
4" perforated perimeter drain

4" gravel pad (no fines)
Filter fabric
Undisturbed native soil or engineered fill as determined by soil conditions
Continuous concrete footing 2'-0" wide and 10'-0" deep
Framing

Advanced Framing, Plywood Sheathing
Exterior Air/Moisture Barrier

Peel-and-stick Membrane Installed Around Entire House, Including Roof
Attic is within Conditioned Space
Exterior Insulation

Two Layers of Two-Inch Thick Extruded Polystyrene Installed on Exterior Side of Weather Barrier
Radiant Floor Heating System

Slab Insulation in Place, Radiant Tubing Installed Undergoing Pressure Test
Occupant Simulation

- Residential Energy Use Highly Dependent Upon Occupant Behavior
- As a Test Facility/Test Bed Need Controlled/Repeatable Conditions
- Usage Schedule Controlled by Computer in Detached Garage
- Devices Turn “on” and “off” According to Occupancy Schedule
- Simulating a Family of Four: Two Adults, Two Children
  - Water Usage
  - Appliances
  - Plug Loads
  - Sensible and Latent Heat Generated by People

Load Simulators
Occupant Comfort

- Sensors installed to capture occupant comfort
  - Air Temperature
  - Relative Humidity
  - Radiant Temperature

Sensors to Monitor Thermal Comfort

Thermal Comfort Sensor Apparatus Placed in Middle of Bedroom
Heating, Cooling, and Ventilation Systems

- Air-to-Air Heat Pump System with Dedicated Dehumidification
- Geothermal Heat Pump System
- Multi-Split Heat Pump
- Heat Recovery Ventilator System with Independent Duct System
Ground Source Heat Exchangers

**Vertical Borehole**
- 3 parallel circuits
- 150' deep, 6” diameter boreholes
- 20’ spacing

**Horizontal Slinky**
- 3 parallel circuits
- 130’ long, 5’ X 5’ trenches
- 10’ spacing
- Loops have 6’ pitch

**Horizontal U-Tube**
- 3 parallel circuits
- 112’ long, 6’ deep trenches
- 10’ spacing
- Each circuit uses 2 trenches
Water Heating System

Preheat - Solar thermal
- 80-gal tank
- Forced-circulation system with heat exchanger
- Four solar thermal flat-plate collectors
- Wi-Fi enabled controller with data storage

Auxiliary - Heat pump water heater
- 50-gal tank
- Energy Factor (EF) of 2.33
- Multiple operating modes: heat pump, hybrid, standard electric
Year-to-Date Performance

<table>
<thead>
<tr>
<th>Total Hot Water Energy Delivered</th>
<th>3427 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Electrical Energy Used</td>
<td>1422 kWh</td>
</tr>
<tr>
<td>Solar Fraction (SF)(^1)</td>
<td>0.54</td>
</tr>
</tbody>
</table>

1. The Solar Fraction is the contribution of solar thermal water heating to the total hot water energy delivered.
Solar Photovoltaic Array

Photovoltaic Array on Main Roof – Rated 10.2 kW at Standard Test Conditions
Solar Photovoltaic System Performance

- **Roof Mounted**
  - PV modules in same plane as roof (18 degrees)
  - 10.2 kW DC Output at Rating Conditions
- **Balance of System**
  - 2 DC-to-AC inverters
  - Grid interconnected (no batteries)

**Conversion Efficiencies**

- **Array:** Sunlight-to-DC
- **Array + Inverter:** Sunlight-to-AC
- **Inverter:** DC-to-AC

**Average Daily Solar System AC Output**

- 19.6% rated efficiency module using mono-Si back-contact cells
NZERTF Heat Pump Performance

Fully Instrumented to Capture Thermal Performance and to Assist in Development of Automated Fault Detection
Daily Energy Performance
July 2013 – June 2014

Daily Exported/Imported Electrical Energy

Cumulative Net Export as of 06/30/14: 491 kWh
Energy Consumption by Category

- Heating, Cooling, Ventilation: 54% 7298 kWh
- Plug Loads: 18% 2440 kWh
- Appliances: 14% 1867 kWh
- Water Heating: 11% 1428 kWh
- Lighting: 3% 435 kWh
Appliance Energy by Category

- **Clothes Dryer**
  - 29%
  - 542 kWh

- **Refrigerator**
  - 22%
  - 410 kWh

- **Oven**
  - 20%
  - 377 kWh

- **Cooktop**
  - 12%
  - 230 kWh

- **Microwave**
  - 8%
  - 141 kWh

- **Dishwasher**
  - 5%
  - 96 kWh

- **Clothes Washer**
  - 4%
  - 71 kWh
So What Did We Learn?
Solar Panels Do Not Perform Well When Snow Covered!
Effect of Snow Cover

- PV Array Covered by Snow for 38 Days
- Well Insulated Roof - Reduced Rate of Melting
- Solar Hot Water Panels Benefited from Dripping Snow Melt
Snow Cover on PV Arrays

- Partial Coverage ≠ Partial Output
- Partial Coverage → Essentially No Output
Ventilation is Essential

- “Build Tight, Ventilate Right”
- Home has a Fully Ducted Ventilation System to Bring in Outdoor Air and Exhaust Indoor Air
- Two Air Streams Exchange Heat through a Heat Recovery Ventilator
- 80% Effectiveness in Exchanging Heat
Beware of Heat Losses in Water Distribution Systems

- Two Tank Water Heating System
  - Solar Preheat Tank Provides Water to …. 
  - Backup Heat Pump Water Heater

- Example - Piping Between Two Tanks
- Many Hot Water Uses in Homes are Small (e.g., Washing Hands)
- No time for Water from Preheat Tank to Reach Backup Tank
Shorten Pipe Runs, Insulate Piping

Normalized Heat Pump Water Heater Inlet Temperature

Delay Time for Heated Water from Solar Tank Reduced
Vampire Electric Loads Add Up

- Many Devices Use Very Small Currents
- But...these loads add up
- Refrigerator, electronics, washer, dryer, dishwasher, microwave, etc.
- Standby load in NZERTF amounted to approximately 84 W ( $10/Month)
The Computer Isn’t Always Right!

- House Performance was Simulated Using the Leading Building Energy Modeling Software
- All Computer Models have Inherent Assumptions
- Energy Models Require User Input
  - Equipment Performance Characteristics
  - Weather Data
  - Details of Construction
The Computer Isn’t Always Right!

Predicted Versus Actual Photovoltaic Energy Production

Percent Difference (Model - Actual) / Actual

-35% -30% -25% -20% -15% -10% -5% 0% 5% 10% 15% 20% 25% 30% 35%

July August September October November December January February March April May June
The Computer Isn’t Always Right!

Predicted Versus Actual Electricity Consumption

Percent Difference
(Model - Actual) / Actual

-35%
-30%
-25%
-20%
-15%
-10%
-5%
0%
5%
10%
15%
20%
25%
30%
35%

July August September October November December January February March April May June
Good Heat Pump, Bad Thermostat

- Air-Source Heat Pump Used for Net-Zero Energy Demonstration
- Installed Unit Sized Correctly and Very Efficient

- Requires Approximately 1 Unit of Electricity to Move 3 Units of Heat
- Drawbacks:
  - Performance worsens as outdoor temperature drops
  - Capacity to deliver heat is limited

These issues necessitate a backup electric resistance element, which provides one unit of heat for each unit of electricity (inefficient)
Thermostat Operation

- Thermostat Determines if Backup Resistance Heat is Needed
- Thermostat Called for Resistance Heat when Heating Needs Could Have Been Met with Heat Pump
- Major Negative Impact on Energy Consumption

Significant time spent in inefficient heating mode
Summary

- Despite Challenging Winter, NZERTF Produced More Energy Than it Consumed
- All Technologies are Commercially Available
- The Approaches Can be Implemented Today
- Future Use of Facility
  - Develop Test Methods for Energy Technologies and Renewables
  - Develop Performance Metrics
  - Evaluate New Building Energy Technologies

- Additional Information:  http://www.nist.gov/el/nzertf
Thank You!

Dad and I after installing solar hot water system at my parents home. Provided hot water for 26 years!


Questions?